# ENHANCED SAFETY OF HEAVY VEHICLES BY USE OF AUTOMATIC CONTROL

**SZCZEPANIAK Cezary**
**SZOSLAND Andrzej**
Vehicle Research Institute
Technical University of Lodz
Poland
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## ABSTRACT

Automatic control of vehicle motion systems has a great influence on enhanced safety. The purpose of presented analysis is to present the possibility of improving vehicle performances by using automatic devices fitted to a vehicle. This paper presents the results of investigations of intelligent control of braking, steering, suspension and power transmission systems of a vehicle, which is equipped with an antilocking braking device (ABS) and traction control one (TCS), active suspension (AS) and four wheel steering (4WS). The dynamics of vehicle was analysed in different road conditions. The solution of equations describing mathematical models was achieved numerically. Its correctness was checked by the comparison of the results of calculation with these ones obtained from the road tests.
The algorithms of the control of all devices are proposed and realised by means of the fuzzy logic method. It outlines the process used to create fuzzy sets and the rules that define the fuzzy controller. The results of the simulation outline enhancement of vehicle performances while using electronic control systems.

**Key words:** motor vehicle, fuzzy control, four wheel steering, antilocking device, active suspension, traction control

## NOTATION

a - distance from c.g. to front axle
b - distance from c.g. to rear axle
C - stiffness of wheel suspension
dz - velocity of vertical displacement of a given mass
$F_{A,O}$ - outside forces: aerodynamic (A) and centrifugal (O)
$F_{Z,X,Y}$ - vertical (z), longitudinal (x) and lateral (y) forces acting on a wheel
h - height of c.g.
K - dampness of wheel suspension
$K_\delta$ - steering angle coefficient
L - wheel base
M - mass of vehicle body
$m_k$ - mass of wheel
R - radius of wheel
t - time
x - longitudinal displacement of c.g.
y - lateral displacement of c.g.
z - vertical displacement of c.g.
$z_{ki}$ - vertical displacement of particular wheel (i=1,2,3,4)
V – linear vehicle velocity
$\Phi$ - pitch angle
$\Psi$ - yaw angle
$\Theta$ - roll angle
$\Omega$ - wheel rotational speed
$\delta_P$ - steer angle of front wheels
$\delta_T$ - steer angle of rear wheels
$\beta$ - side-slip angle of c.g., wheels
$\mu$ - surface adhesion coefficient

## 1. INTRODUCTION

To improve a road safety is typical for the contemporary needs. This is a reason for applying to a vehicle different devices which help the driver to control a vehicle motion, and sometimes even replace his action. Before equipping a vehicle with these devices it is necessary to define an influence of their properties on dynamic performances of a vehicle .
The paper presents some results of the investigations carried out in Vehicle Research Institute which refers to dynamics of the motor vehicles equipped with control devices, which influence upon a vehicle motion. Among them can be mentioned ABS - antilocking device, TCS - traction control, AS - active suspension or 4WS - four wheel steering.
The principal aim of the investigations is to estimate an effect of the operation of all automatic devices, even in the case when all of them work at the same time. The results of the investigations gave the information according to the integration of ABS, TCS, AS and 4WS into one, common control system of vehicle dynamics.
The control algorithms of mentioned devices are realised using a fuzzy logic theory [9]. It allows to

formulate the relationship between the input and the output signals of the controller and taking into account the human knowledge about controlled processes. Advances in microelectronics and actuators make much it easier.

Recently, fuzzy logic theory has been incorporated into many market products and to automotive technologies as well [3], [4], [8]. Using fuzzy logic simplify detailed models of particular subsystems. It happens so, because using fuzzy controllers needs to define rather the relationship between input and output signals, than the parameters that describe the dynamics of the system.

## 2. VEHICLE MODEL

For the dynamic description of the analysed system, the physical model of a vehicle was assumed as a spatial discreet system of elastically joined lumped masses. It was assumed that the masses of wheels do not displace longitudinally with respect to the chassis and they move forward together with the mass of a body. The displacement of them, in accordance to a chassis, is allowed in vertical direction, in compliance with stiffness of a tyre and a suspension system.

The external forces acting on a vehicle are as shown in Fig.1:

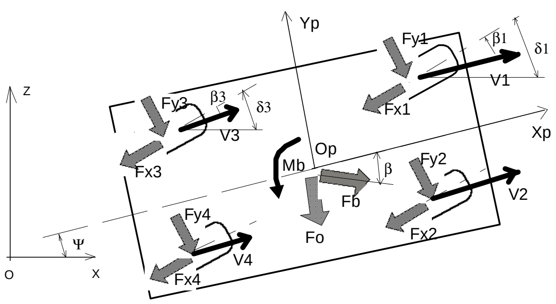


Fig.1 Physical model of a vehicle

Vehicle motion is defined with reference to a right-hand co-ordinate system $OX_PY_PZ_P$ with originates at its centre of gravity. It allows to describe car longitudinal. lateral and vertical motion, as well as roll about $X_P$ axis, pitch about $Y_P$ axis and yaw about $Z_P$ axis. Vehicle trajectory is defined with respect to a right-hand orthogonal axis system OXYZ fixed on the earth. All wheels - front and rear can be steered in both directions.

It is assumed that the motion takes place on a flat, smooth surface, along the curvilinear path. Two principles of curvature are taken into consideration: changing the lane and steady state cornering.

The relations describing the non-linear characteristics of the tyres are based on Dugoff's hypothesis, adapted to the parameters of considered vehicle.

The model of driver is limited to begin the process of changing the direction of motion only and not interrupting its performance. The driver is treated as an 'ideal regulator', which does not correct his action.

## 3. AUTOMATIC DEVICES – GENERAL CONCEPT

### 3.1. ANTILOCKING - ABS

The solution of ABS used in the analysis is a three-stage device. When it is fitted to a vehicle it can work in SL,SH and IC modes. Its parameters describe a real solution, designed and developed in the Vehicle Research Institute. It was designated for pneumatic braking systems and used in buses, trucks and trailers. The construction is an add-on solution, which does not change the principal braking system and allows to brake a vehicle conventionally in the case when the ABS is switched off.

The general concept of functioning is to follow the angular velocity of each wheel and to compare it with 'programmed velocity', which represents the velocity of vehicle. When the electronic control unit states the tendency of a particular wheel to be locked, the braking pressure is decreased in such wheel, what protects the wheel against locking.

### 3.2. TRACTION CONTROL – TCS

The discussed solution of TCS allows to follow the power transmitted to the wheels and to reduce it in a case of appearing the surplus of longitudinal forces in comparison to the adhesion. The realisation of this purpose is done by means of applying the braking torque in any of driven wheels and/or the power transmitted from an engine. The electronic control unit compares the angular speed of each driven wheel with the velocity of vehicle. When the slip during acceleration increases, the braking actuator is activated and the injection fuel pump is cut off.

### 3.3. SUSPENSION CONTROL - AS

The comfort and the safety of the ride depend strongly on the variations of the positions of the vehicle body, which are determined by outside disturbances. These disturbances can take the form of irregularities of the surface, as well as be called the inertia forces, which appear during braking, accelerating or a curvilinear drive.

When there is a danger of loss of the vehicle stability it is necessary to fit suspension elements with changeable characteristics. These features are typical for active suspensions, which generally are used to minimise the vibrations of sprung masses as well to assure the permanent contact between the tyre and the road. In effect it makes it easier to control the vehicle [1].

The described activity is possible due to the change of energy dissipation, by means of the changes of stiffness of the spring elements *C* and the dampness of the shock absorbers *K*. This can be done by the regulation of the flow area of the absorber, the activity of additional spring elements or the change of force in an added actuator. The actuator can be added parallel to the suspension elements or replace them totally.

### 3.4. 4WS CONTROL DEVICE

All wheels **-** front and rear can be steered in both directions, with following limitations caused by steering system: $-\delta_Z \leq \delta_{1,3} \leq \delta_W$ $\quad -\delta_W \leq \delta_{2,4} \leq \delta_Z$ where $\delta_{Z,W}$ are the maximum steering values of inner and outer wheel.

The obtained effects depend on the direction of steer angle of a wheel [2]. The trajectory of motion is the result of the relation between the turn of front and rear wheels. This ratio is designed by a non-linear coefficient depending on speed $K_\delta = \delta_T / \delta_P$. It is assumed that $K_\delta$ is positive, when all wheels are steered in the same direction, the negative **-** when in opposite direction.

## 4. FUZZY LOGIC CONTROL OF THE DEVICES

The philosophy of the control of the devices is to register the input signals from the sensors and generate the output signals. The sensors follow the signals of angular velocities of wheels, vehicle speed, the displacement of the suspension, steering angle etc. The output signals can force the operation of braking modulators, fuel pump, shock absorbers etc. The technical realisation of the control unit is prepared by means of fuzzy logic theory. It operates using the fuzzy sets describing input and output physical signals. Any particular variable can be represented by unique fuzzy set. In the presented principle the angular velocity of the wheel (WV) and vehicle velocity represented by 'programmed" one (VV), suspension deflection (DS), its velocity (VS), tyre deflection (DW), the steering angle of front wheels (LKP*)*, vehicle velocity (LPR*)*, coefficient K□ (LKD). They are assumed in a form:

*LWV* = {ZE,PS,PE,PM,PB,PU,PV}
*LVV*= {NB,NM,NE,ZE,PS,PE,PM,PB}
*LDS* = {PB,PM,PS,ZE,NS,NM,NB}
*LVS* = {PB,PM,PS,ZE,NS,NM,NB}
*LDW* = {PS,ZE,NS}
*LPR* = {ZE,PS,PM,PB,PU,PLB,PUB,PEB}
*LKP*={NE,NLB.NU,NB,NM,NS,ZEN,ZEP,PS,PM, PB,PU,PL,PE}
*LKD* = {ZE,PS,PM,PB,PU,PLB,PUB,PEB}

The triangle Λ, gamma Γ and L shapes of fuzzy subsets are here involved. The continuous area of particular functions is quantified into determined quantity of segments relative to the assumed signals levels.

It is assumed the following fuzzy subsets describing above variables as follows: zero (ZE), positive small (PS), positive medium (PM), positive big (PB), negative big (NB), negative medium (NM) etc.

The output signals are the values of control of particular wheel brake modulator (MH), power torque (MN), actuator force (U) of particular active suspension, the steering angle of rear wheels (KT) . They are represented by following fuzzy sets:

*LMH*= {PO,ZE,NE}
*LMN* = {PO,ZE,NE}
*LU* = {PB,PM,PS,ZE,NS,NM,NB}
*LKT*={NL,NU,NB,NM,NS,ZE,PS,PM,PB,PU,PL }

The graphical presentation of principle fuzzy sets are shown in Fig. 2.

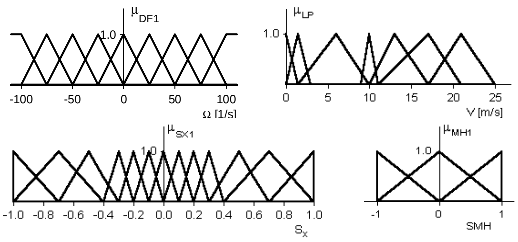


Fig 2. Fuzzy sets of LVV, LWV, LWS and LMH

The control algorithms realise the relationship between inputs and outputs. It can be created by the use of descriptive phases rules. These rules determine the fuzzy controller.

For ABS 35 logic rules have been prepared, using the fuzzy controller. Some principles of them:

if (VV) is (ZE) and (WV) is (NB) then (MH) is (NE);
if (VV) is (PE) and (WV) is (NS) then (MH) is (PO);
if (VV) is (PB) and (WV) is (PS) then (MH) is (ZE);
etc.

For TCS 98 logic rules have been prepared, using the fuzzy controller. Some principles of them:

if (SX1) is (ZE) and (DF2) is (NB) and (VB) is (PO) then (MS) is (NE);
if (SX1) is (ZE) and (DF2) is (NB) and (VB) is (PO) then (MH) is (NE);
if (SX1) is (PE) and (DF2) is (NS) and (VB) is (PO) then (MS) is (NE);
if (SX1) is (PE) and (DF2) is (NS) and (VB) is (PO) then (MH) is (PO);
etc.

For 4WS 49 logic rules have been prepared. Some principles of them are:
if (DS) is (ZE) and (VS) is (ZE) then (U) is (ZE);
if (DS) is (ZE) and (VS) is (NS) then (U) is (PS);
if (DS) is (NS) and (VS) is (PS) then (U) is (NS);
if (DS) is (NS) and (VS) is (NS) then (U) is (PS);
if (DS) is (NB) and (VS) is (PB) then (U) is (PB);
if (DS) is (NB) and (VS) is (PS) then (U) is (PM);
etc.

For 4WS 196 rules where prepared for control algorithm. Some exemplary of them:
if (KP) is (ZE) and (KD) is (PEB) then (KT) is (ZE);
if (KP) is (PB) and (KD) is (PUB) then (KT) is (PB);
if (KP) is (PLB) and (KD) is (PU) then (KT) is (PLB);
if (KP) is (NB) and (KD) is (PB) then (KT) is (NM);
if (KP) is (NUB) and (KD) is (PM) then (KT) is (NEB);
etc.

The output of each rule is aggregated into simple fuzzy set for the overall output. The defuzzyfying process allows to calculate a real output signal. It changes the output subsets and associated levels for all rules into real signal.

## 5. THE RESULTS OF INVESTIGATIONS

The correctness of assumed model was checked by means of simulation researches. The principle of driving on a straight lane on different kinds of surface was taken into consideration as a presentation of obtained results, although some other tests were also carried out.
The parameters of vehicle described heavy vehicle domain characteristics. Its weight was approx. M=10000 kg, wheel base L=6.1 m, a distance from c.g. to front axle a=3.9 m, rear one b=2.2 m. The height of gravity centre h=1.5 m and wheel radius R=0.488 m.
The tests were performed for homogeneous conditions -high value of adhesion coefficient, low value of adhesion coefficient as well as for μ-split conditions (the adhesion coefficient was different for left and right wheels of vehicle). For such circumstances numerical calculation allowed to obtain the results which could be compared with road experiments. Fig. 3 shows the results of calculation of braking process. The velocity of a vehicle (V), velocities of its front wheels ($V_1$) as well as the longitudinal $F_X$ forces are presented in the diagram.

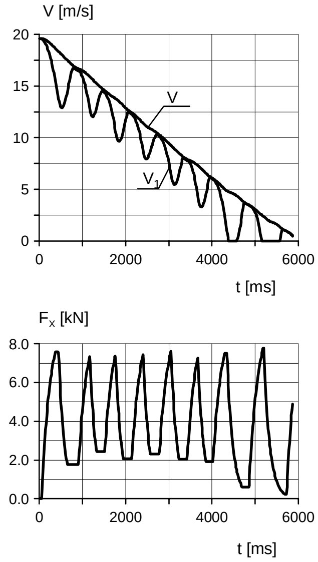


Fig.3 Braking on the straight path

Automatic control systems discussed so far were the systems which operate usually independently of each other. It seemed to be profitable to connect them into one, collective system. To know the possibilities of such integration it iwa necessary to describe a mutual influence of particular systems in various vehicle dynamic states.
Simultaneous operation of investigated automatic systems were also tested [5], [6], [7].
Fig.4 shows the results of braking with ABS and AS operation (on the left side of the diagram) and braking with ABS and 4WS (on the right side). The diagram presents calculated longitudinal $F_X$ and lateral $F_Y$ forces appearing on the wheels. The outside circle represents the maximum theoretical values of these forces, which could be obtained in accepted road conditions. The inside curve (dotted area) covers a typical region of available forces during conventional braking of a vehicle without ABS. The outer lines (thick) shows temporary values of the shear forces which can be available during braking with antilocking device.
Fig.5 shows the obtained results of accelerating with ASR and 4WS.

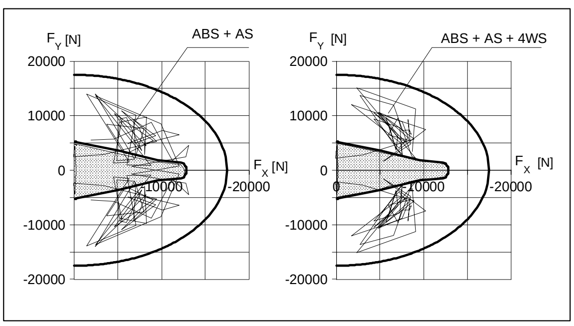


Fig.4 Braking of a vehicle with ABS, AS and 4WS

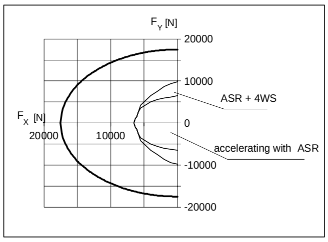


Fig.5 Accelerating of a vehicle with ASR and 4WS

These are the examples of simultaneous operation of control systems of braking, accelerating, steering the wheels or changing the suspension characteristics.
The presented results are very interesting however they describe only a part of sophisticated road conditions during braking, accelerating or steering. As a reason of that, there are the situations when more than two devices work at the same time, e.g. ABS, AS and 4WS or ASR, AS and 4WS. The simultaneous operation of ABS and ASR is impossible.

## 6. CONCLUSIONS

Presented models allows to estimate the dynamic performances of vehicle during motion. Results of the simulation were compared with the results of experiments. It can give an opinion about the compliance of assumed model with real physical object and to confirm the correctness of computation procedure. it also can be treated as one of the method which allows to define the dynamic properties of a vehicle in different road conditions.

Basing on identified model of vehicle a method of simulation studies allows to estimate the concepts of control of different devices influences upon vehicle motion, veryfing the structure of regulators or selection of their parameters.

The analysis of the simulation shows that the simultaneous action of ABS, AS and 4WS, as well ASR, AS and 4WS improves the performance of a vehicle. A driver is supported in dangerous situations, such as rapid braking, acceleration or vehicle skid.
Operation of particular systems does not disturb each other.

We know that describing all aspects of assumed models is not possible in this paper. It is the reason that they are presented only in a very short form. The aim of our researches was to show that integrated automatic control is possible and it has a great influence on enhanced safety. Maybe not all mentioned devices must be incorporated into a vehicle (e.g. 4WS) but their appearance ensures the intelligence features of vehicle.

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